

Baryon resonances in the strangeness production

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We have studied the $N^*(2120)$, $\Delta^*(1940)$, and the possible $\Sigma^*(1380)$ resonances in the $\gamma p \rightarrow K^+\Lambda(1520)$, $pp \rightarrow nK^+\Sigma(1385)$, and $\Lambda p \rightarrow \Lambda p\pi^0$ reactions within the resonance model and the effective Lagrangian approach. It is shown that when the contributions from these baryonic states were considered, the current experimental measurement could be well reproduced. In addition, we also demonstrate that the angular distributions provide direct information of these reactions, which could be useful for the investigation of those states and may be tested by future experiments.

KEYWORDS: Baryon resonances, effective Lagrangian approach, strangeness production

1. Introduction

The associate production of hadrons by photon and hadron beams has been extensively studied since it provides an excellent tool to learn the details of the hadron spectrum. In addition, those reactions require the creation of an $\bar{s}s$ quark pair. Thus, a thorough and dedicated study of the strangeness production mechanism in those reactions has the potential to gain a deeper understanding of the interaction among strange hadrons and also the nature of the baryon resonances. In particular, the $\gamma p \rightarrow K^+\Lambda(1520)$ reaction is an efficient isospin 1/2 filter for studying nucleon resonances decaying to $K\Lambda(1520)$. As a consequence, the experimental database on this reaction has expanded significantly in recent years. For the $pp \rightarrow nK^+\Sigma^+(1385)$ reaction, it has a special advantage for studying the Δ^* resonance since there is no contribution from isospin 1/2 nucleon resonances because of the isospin and charge conservations. For the $\Lambda p \rightarrow \Lambda p\pi^0$ reaction, it is a very good isospin one filter for studying Σ^* resonances decaying to $\pi\Lambda$, and provides a useful tool for testing Σ^* baryon models.

Both on the experimental and theoretical sides, the nucleon and Δ^* resonances around or above 2.0 GeV and the hyperon excited states have not been extensively studied [1]. For example, the first $\Sigma(1193)$ excited state, $\Sigma^*(1385)$, was cataloged in the baryon decuplet of the traditional quark models which still have some problems for the excited baryon resonances. Recently, the penta-quark picture [2,3] provides the natural explanation for the baryon states [4]. Indeed, the new observation of the heavy hidden charm baryonic P_c^+ states [5] has challenged the conventional wisdom that baryons are composed of three quarks in the naive quark model.

Based on the penta-quark picture, a newly possible Σ^* state, $\Sigma^*(1380)$ ($J^P = 1/2^-$) was predicted around 1380 MeV [6]. Besides, another more general penta-quark model [2] without introducing explicitly diquark clusters also predicts this new Σ^* state around 1405 MeV. Obviously, it is helpful

to check the correctness of penta-quark models by studying the possible $\Sigma^*(1380)$ state. Because the mass of this new Σ^* state is close to the well established $\Sigma^*(1385)$ resonance, it will make effects in the production of $\Sigma^*(1385)$ resonance and then the analysis of the $\Sigma^*(1385)$ resonance suffers from the overlapping mass distributions and the common $\pi\Lambda$ decay mode.

In this paper, we will review the main results from those theoretical studies about the $N^*(2120)$, $\Delta^*(1940)$, and the possible $\Sigma^*(1380)$ resonances. In next section, we show the results for the $N^*(2120)$ resonance in the $\gamma p \rightarrow K^+\Lambda(1520)$ reaction. In section 3, we study the role of $\Delta(1940)$ in the $pp \rightarrow nK^+\Sigma(1385)$ reaction, while in section 4, we investigate the possible $\Sigma^*(1380)$ in the $\Lambda p \rightarrow \Lambda p\pi^0$ reaction. Finally, a short summary is presented in the last section.

2. Study on $\gamma p \rightarrow K^+\Lambda(1520)$ reaction

For the $\gamma p \rightarrow K^+\Lambda(1520)$ reaction, the differential cross section, in the center of mass frame (c.m.), and for a unpolarized photon beam reads [7],

$$\frac{d\sigma}{d(\cos\theta_{\text{c.m.}})} = \frac{|\vec{k}_1^{\text{c.m.}}||\vec{p}_1^{\text{c.m.}}|}{4\pi} \frac{M_N M_{\Lambda^*}}{(W^2 - M_N^2)^2} \sum_{s_p, s_{\Lambda^*}, \lambda} |T|^2, \quad (1)$$

with W the invariant mass of the γp pair. Besides, $\vec{k}_1^{\text{c.m.}}$ and $\vec{p}_1^{\text{c.m.}}$ are the photon and K^+ meson c.m. three-momenta, and $\theta_{\text{c.m.}}$ is the K^+ polar scattering angle. The invariant scattering amplitudes are defined as

$$-iT_i = \bar{u}_\mu(p_2, s_{\Lambda^*}) A_i^{\mu\nu} u(k_2, s_p) \epsilon_\nu(k_1, \lambda), \quad (2)$$

where u_μ and u are dimensionless Rarita-Schwinger and Dirac spinors for final $\Lambda(1520)$ and the initial proton, respectively, while $\epsilon_\nu(k_1, \lambda)$ is the photon polarization vector. Besides, s_p and s_{Λ^*} are the baryon polarization variables. The sub-index i stands for the contact, t -channel K^- exchange, s -channel nucleon pole and N^* resonance terms [8], and the u -channel $\Lambda(1115)$ contribution [9].

In Fig. 1, we show the differential cross section as a function of the LAB frame photon energy and for different forward c.m. K^+ angles. The experimental data are taken from LEPS [10] and CLAS [11]. The blue-dashed curve stands for the contributions from t -channel K^- exchange, s -channel nucleon pole and u -channel $\Lambda(1115)$ terms. The black-dash-dotted curves stand for the contribution from the Reggeon exchange mechanism. The green-dotted lines show the contribution of the $N^*(2120)$ resonance term, while the red-solid lines stand for the full contributions. One can see that our results can describe the experimental data very well.

3. Study on the $pp \rightarrow nK^+\Sigma^+(1385)$ reaction

The full invariant scattering amplitude for the $pp \rightarrow nK^+\Sigma^+(1385)$ reaction is composed of two parts corresponding to the s -channel $\Delta^*(1940)$ resonance, and u -channel $\Lambda(1115)$ hyperon pole, which are produced by the π^+ -meson exchanges, $\mathcal{M} = \mathcal{M}_s + \mathcal{M}_u$ (more details can be found in Ref. [12]). Here we give explicitly the amplitude \mathcal{M}_s , as an example,

$$\begin{aligned} \mathcal{M}_s = & \frac{\sqrt{2}g_{\pi NN}g_{\pi N\Delta^*}}{m_\pi} F_\pi^{NN}(k_\pi^2) F_\pi^{\Delta^*N}(k_\pi^2) F_s(q_s^2) G_\pi(k_\pi^2) \bar{u}^\mu(p_4, s_4) \left(-\frac{g_1}{m_K} p_5 g_{\mu\rho} + \frac{g_2}{m_K^2} p_{5\mu} p_{5\rho} \right) \times \\ & G_{\Delta^*}^{\rho\sigma}(q_s) k_{\pi\sigma} \gamma_5 u(p_1, s_1) \bar{u}(p_3, s_3) \gamma_5 u(p_2, s_2) + (\text{exchange term with } p_1 \leftrightarrow p_2), \end{aligned} \quad (3)$$

where s_i ($i = 1, 2, 3$) and p_i ($i = 1, 2, 3$) represent the spin projection and 4-momenta of the two initial protons and final neutron, respectively. While p_4 and p_5 are the 4-momenta of the final $\Sigma^+(1385)$ and K^+ meson, respectively. And s_4 stands for the spin projection of $\Sigma^+(1385)$. In Eq. (3), $k_\pi = p_2 - p_3$

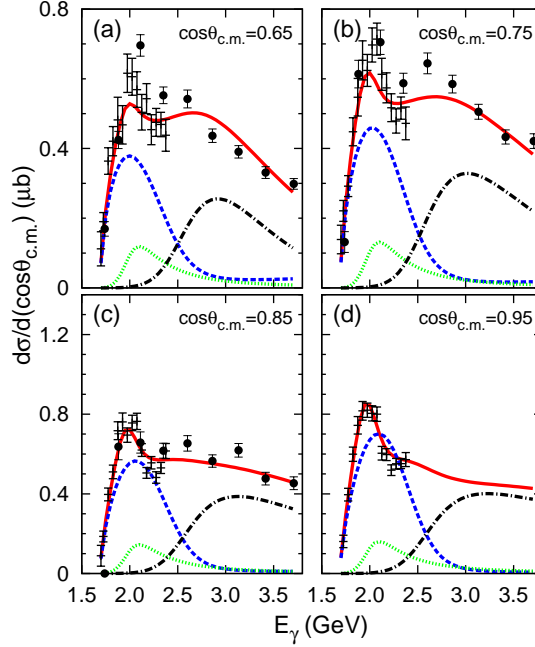


Fig. 1. (Color online) The $\gamma p \rightarrow K^+ \Lambda(1520)$ differential cross section as a function of the LAB frame photon energy for different c.m. K^+ polar angles.

and $q_s = p_4 + p_5$ stand for the 4-momenta of the exchanged π^+ meson and intermediate $\Delta^*(1940)$ resonance. The $G_\pi(k_\pi^2)$ and $G_{\Delta^*}^{\rho\sigma}(q_s)$ are the pion and $\Delta^*(1940)$ propagators, which have the forms as,

$$G_\pi(k_\pi^2) = \frac{i}{k_\pi^2 - m_\pi^2}, \quad (4)$$

$$G_{\Delta^*}^{\rho\sigma}(q_s) = \frac{i(q_s + M_{\Delta^*})}{q_s^2 - M_{\Delta^*}^2 + iM_{\Delta^*}\Gamma_{\Delta^*}} \left(-g^{\rho\sigma} + \frac{1}{3}\gamma^\rho\gamma^\sigma + \frac{2}{3M_{\Delta^*}^2}q_s^\rho q_s^\sigma + \frac{1}{3M_{\Delta^*}}(\gamma^\rho q_s^\sigma - \gamma^\sigma q_s^\rho) \right), \quad (5)$$

where M_{Δ^*} and Γ_{Δ^*} are the mass and total decay width of the $\Delta^*(1940)$ resonance, respectively.

Furthermore, we need also the relevant off-shell form factors for πNN and $\pi N\Delta^*$ vertexes, which have been already included in the amplitude of Eq. (3), and we take them as,

$$F_\pi^{NN}(k_\pi^2) = \frac{\Lambda_\pi^2 - m_\pi^2}{\Lambda_\pi^2 - k_\pi^2}, \quad F_\pi^{\Delta^*N}(k_\pi^2) = \frac{\Lambda_\pi^{*2} - m_\pi^2}{\Lambda_\pi^{*2} - k_\pi^2}, \quad F_s(q_s^2) = \frac{\Lambda_s^4}{\Lambda_s^4 + (q_s^2 - M_{\Delta^*}^2)^2}, \quad (6)$$

with k_π the 4-momentum of the exchanged π meson. The cutoff parameters are taken as $\Lambda_\pi = \Lambda_\pi^* = 1.1$ GeV and $\Lambda_s = 0.9$ GeV, with which the experimental data on $pp \rightarrow nK^+\Sigma^+(1385)$ reaction can be reproduced.

Then, we can easily obtain the total cross sections for $pp \rightarrow nK^+\Sigma^+(1385)$ as,

$$d\sigma = \frac{m_p^2 m_n m_{\Sigma^+(1385)}}{256\pi^5 \sqrt{(p_1 \cdot p_2)^2 - m_p^4}} \sum_{s_1, s_2, s_3, s_4} |\mathcal{M}|^2 \frac{d^3 p_3}{E_3} \frac{d^3 p_4}{E_4} \frac{d^3 p_5}{E_5} \delta^4(p_1 + p_2 - p_3 - p_4 - p_5). \quad (7)$$

The total cross section versus the beam momentum are shown in Fig. 2. The dotted, and dash-dotted lines stand for contributions from $\Lambda(1115)$ and $\Delta^*(1940)$ resonance, respectively. Their total

contributions are shown by the solid line. From Fig. 2, we can see that the contribution from the $\Delta^*(1940)$ resonance is predominant in the whole considered energy region. For comparison, we also show the experimental data [13, 14] in Fig. 2, from where we can see that our predictions for the total cross sections of $pp \rightarrow nK^+\Sigma^+(1385)$ reaction are in agreement with the experimental data.

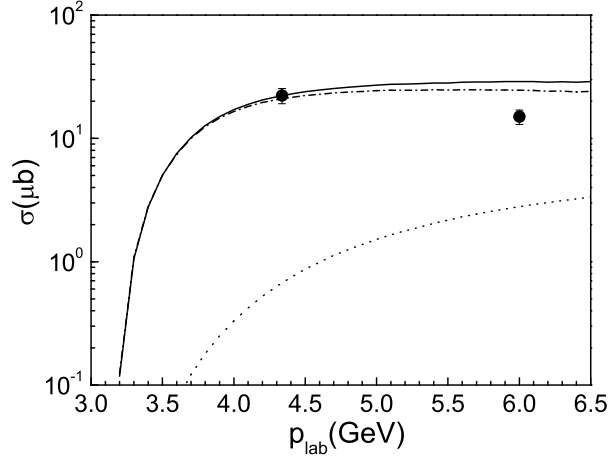


Fig. 2. Total cross sections vs beam energy p_{lab} of proton for the $pp \rightarrow nK^+\Sigma^+(1385)$ reaction.

4. Study on the $\Lambda p \rightarrow \Lambda p \pi^0$ reaction

The theoretical results (see more details in Ref. [16]) of the total cross section for the $\Lambda p \rightarrow \Lambda p \pi^0$ reaction versus the beam momentum are shown in Fig. 3, where the contributions of $\Sigma^*(1385)$ resonance, $\Sigma^*(1380)$ state, nucleon pole and $\Sigma(1193)$ pole to the energy dependence of the total cross section are shown by dashed, dotted, dash-dotted, and dash-dot-dotted curves, respectively. Their total contribution is depicted by the solid line. It is clear that the contributions from the $\Sigma^*(1380)$ state and $\Sigma^*(1385)$ resonance dominate the total cross section at beam momenta below and above 1.3 GeV, respectively, while the contributions of nucleon and $\Sigma(1193)$ pole are small and can be neglected.

The $\Sigma^*(1385)$ resonance with spin-parity $3/2^+$ decays to $\pi\Lambda$ in relative P -wave and is suppressed at low energies. It can not reproduce the near threshold enhancement for the $\Lambda p \rightarrow \Lambda p \pi^0$ reaction. On the contrary, the possible $\Sigma^*(1380)$ state with $J^P = 1/2^-$ is decaying to $\pi\Lambda$ in relative S -wave, which will give enhancement at the near threshold. As one can see in Fig. 3, thanks to the contribution from $\Sigma^*(1380)$ state, we can reproduce the experimental data taken from Ref. [15] for all of the beam energies. Thus, we find a natural source for the near threshold enhancement of the $\Lambda p \rightarrow \Lambda p \pi^0$ reaction coming from the possible $\Sigma^*(1380)$ state which decays to $\pi\Lambda$ in the S -wave.

5. Summary

The combination of effective Lagrangian approach and isobar model is an important theoretical tool in describing the various processes in the region of baryon resonance production. In this paper, we have shown the results on the studies of the $N^*(2120)$, $\Delta^*(1940)$, and the possible $\Sigma^*(1380)$ resonances in the $\gamma p \rightarrow K^+\Lambda(1520)$, $pp \rightarrow nK^+\Sigma(1385)$, and $\Lambda p \rightarrow \Lambda p \pi^0$ reactions. It is shown that when the contributions from these baryonic states were considered, the current experimental measurement

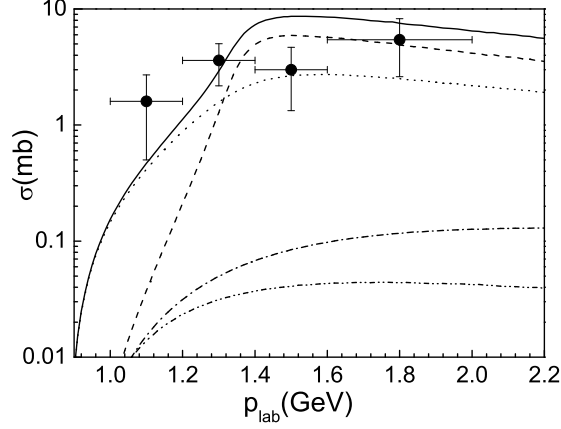


Fig. 3. The total cross sections vs the beam momentum p_{lab} for the $\Lambda p \rightarrow \Lambda p \pi^0$ reaction.

could be well reproduced. In addition, we also demonstrate that the angular distributions provide direct information of these reaction, hence could be useful for the investigation of those states and may be tested by future experiments.

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